Evaluation of the synergies in cogeneration with steel waste gases based on Life Cycle Assessment: A combined coke oven and steelmaking gas case study

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ABSTRACT

Steel making processes dispose large volumes of waste gases whose potential energy can be transformed into heat and electricity by means of cogeneration. A case study using coke oven and Linz-Donawitz converter gas is presented here. The data is obtained from an existing plant located in Northern Spain. The engines are adapted for its operation with converter gas, and steam is generated in boilers that consume coke gas, converter gas and natural gas in the absence of waste gases. The actual influence on the environmental behaviour of the process is analysed considering the benefits but also the drawbacks derived from the gases low calorific value, toxicity and polluting. The work constitutes the first study in an installation with these characteristics and burning this combination of gases. The functional unit is represented by 1 MWh of thermal energy. The analysis has been developed mainly on the bases of the following sources: site-specific measured or calculated data directly from the process of cogeneration, life-cycle inventory databases and bibliographical information. Operating parameters, as well as production data (thermal and electric energy), emissions of NO_X, SO_2 and CO_2, discharges and wastes associated with this process are exposed. The system boundaries were considered gate to gate, so the results are useful for the integration with other global scenarios. Midpoint and endpoint characterisation factors for humans, ecosystems and resources are given. The main effects are related to Climate change, Ionising radiation, Human toxicity and Fossil and Ozone depletion. The results indicate that the usage of these gases implies an environmental benefit. The operational data belonging to 2014 shows a reduction of more than 100 points in the global impact of the functional unit. In the best scenario, 169.42 Nm^3/MWh of natural gas may be saved with the consequent reduction in natural resources and ozone depletion.

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1. Introduction

CO_2 emission is one of the most important issues in Europe nowadays and the steel making sector is very influenced by this context. Many improvements have been made in the iron and steel sectors to increase efficiency and reduce emissions. However, the requirements in this line of action are increasing, and the regulations are more restrictive. The EU Commission's Low Carbon Roadmap anticipates an emissions intensity of less than 0.2t CO_2/t steel compared to the starting levels of 1.3t CO_2/t steel (Höglund-Isaksson et al., 2012). Regardless of whether it is realistic to achieve these objectives, the steel making sector will require both technical and financial breakthroughs in technology to ensure its sustainability.

In the current context, it is very important for large consumers of energy (like the steel making sector) to generate, even partially, their own energy requirements. The energy consumed in the entire steel production process represents a very significant percentage of the economic and environmental costs (between 20% and 40% in some countries). Approximately 50% of this energy comes from coal, 5% from natural gas and 5% from other gases (World Steel

Association, 2017). One key technology in order to pursuit this goal is the utilisation of steel gases for power production. Steel production processes typically dispose large volumes of speciality gases that are recognized to be important for energy production in form of heat and electricity. As pointed by Pan et al. (2016), sustainability could be improved recycling flue gas and recovering heat from emitted waste gas. Several case studies have been described in the literature. For example, Ziebik et al. (2014) analysed the repowering of an existing metallurgical combined heat and power plant fired with low-calorific technological fuel gases mixed with hard coal. Jianwei et al. (2003) describe an oxygen blast furnace and combined cycle. The new process utilizes the top gas of a blast furnace as a process input enabling it to move closer to the goal of zero waste. Modesto and Nebra (2009) have analysed a power generation system using a blast furnace and coke oven gas in a Brazilian steel mill. Olmez et al. (2016) remark the positive effect using coke oven gas because the avoided external energy consumption. Therefore, in view of the foregoing, cogeneration is presented as the solution for the treatment of steel gases by simultaneously reducing atmospheric emissions and the high energy requirements of the major producers of steel, as stated by Bieda (2011) and Modesto and Nebra (2009).

Three different process stages, from coal to steel, provide three different gas types suitable for energy valorisation: coke gas, blast furnace gas and basic oxygen converter gas. However, the low calorific value, low pressure, toxicity and content of dirty and potentially polluting substances in steelmaking gases significantly reduce the technologies available for their use as well as their efficiency (Modesto and Nebra, 2009). This makes the actual influence on the environmental behaviour of the process not entirely obvious and requires an environmental assessment.

There are a considerable number of studies on energy efficiency and CO_2 emission reduction potential in the iron and steel industry, but most of them are focused on the industry and policy making level in different regions (i.e. (Chen et al., 2014; Lin and Wang, 2014; Wen et al., 2014) in China (Karali et al., 2014), in US and (Pardo and Moya, 2013) in Europe). The study published by Zhang et al. (2018) recognizes this gap and they propose a plant-level analysis of the carbon flow of iron and steel mills. There are also a considerable number of Life Cycle Inventories (LCI) and Life Cycle Assessments (LCA) applied to different steel industry processes, but most of them are focused on steel products rather than analyse specific process for the valorisation of gases. For example, Bo et al. (2011) concentrated on evaluate the contributions of four recycling strategies of steel slag, and they take as functional unit 1 kg of crude steel. They consider coke oven gas, but only 32% is used in the system investigated. Burchart-Korol (2013) performs a LCA of steel production through the integrated steel production and electric arc furnace routes in Poland. The functional unit was one ton of cast steel. Renzulli et al. (2016) presented the LCA of steel produced in an Italian integrated steel mill. Özdemir et al. (2017) determine the environmental burdens of steel rebar production with induction melting furnace technology, considering 1 t of steel rebar production as functional unit. Liu and Yuan (2016) have detailed the LCI of coke production in China. They consider the raw oven coke gas treatment in order to be used as a fuel gas, but they do not consider their later valorisation. In summary, most of the previous studies consider the steel gases as a remarkable by-product. However, there are few studies for the energetic valorisation of those gases following the LCA method. In this sense, the contributions from Bieda have detailed the LCI of different energy generation processes in the steel industry in Poland. The LCI of the energy production in a steel power plant in Krakow was described in (Bieda, 2011), where blast furnace gas and coke oven gas where considered among the fuels. The functional unit is represented by the total MW of generated electric and heat energies. The environmental impact of the process of energy generation in a boiler station with hard coal and blast furnace gas is described in (Bieda et al., 2010), indicating that the utilisation of blast furnace gas is always a more advantageous option for the environment than the technology of firing with coal. The process of basic oxygen furnace steel production is also detailed in (Bieda, 2012a) and also the blast furnace pig iron production (Bieda, 2012b) and the continuous casting of steel (Bieda et al., 2018). A LCA is performed to compare the environmental impact of an iron making system with a combined cycle power plant, to a system producing the same amount of electricity in a coal power plant (Li et al., 2017), demonstrating that the first is more environmentally friendly. Van Caneghem et al. (2010) described a case study of an integrated steelwork reduction of its environmental emissions by means of the evolution of 6 partial eco-efficiency indicators for the impact categories acidification, photo-oxidant formation, human toxicity, freshwater aquatic ecotoxicity, eutrophication and water use, but by-product gases are not studied in detail. Messagie et al. (2013) have analysed the LCA for electricity production with blast furnace gas as a case study illustrating an allocation method.

Therefore, after what has been stated in the previous paragraphs, it can be concluded that the LCA applied to the field of energy production has been widely studied, yet no LCA has been applied to the production of energy from the valorisation of steel gases with the combination of this case study (coke oven gas, converter gas and natural gas), so this study constitutes the first work on the LCA of a cogeneration process with these steel gases (SGCP) in an installation with these characteristics.

The main objective of study is to determine if the valorisation of steelmaking gases to a cogeneration process plant represents an environmental benefit despite their negative effects. The results can provide valuable data for more global studies, like the former referenced. They can also be useful for making decisions in global scenarios, like those described in (Zhang et al., 2018) or (Zhao et al., 2017) or global optimisation models, for instance with models to optimize the allocation of surplus waste gases and suitable capacity for buffer users, like the model proposed by Yang et al. (2017), and to find a balance between the cost of increasing the storage capacity of steel gas (increasing gasometers capacity) and the environmental balance finally obtained.

The paper is organised as follows: the materials and methods are presented first, where the study area, the goal and scope, the inventory analysis and the impact assessment categories are described. Next, the analysis and discussion of results is described. And finally, the conclusions and the final recommendations are presented.

2. Materials and methods

The LCA method is widely used to compare the relative environmental performance of competing processes, by analysing the environmental impacts generated by the processes within defined categories and boundaries. The work from Turconi et al. (2013) analysing 167 case studies involving LCA of electricity generation represents a good example of that.

The work has been carried out according to the requirements established by the International Standards Organization ISO 14040—2006. The main steps carried out were: (1) definition of goal and scope; (2) inventory analysis; (3) impact assessment and (4) interpretation. The first three steps are detailed below. The interpretation corresponds to the Results and Discussion section. ReCiPe, developed by RIVM and Radboud University, CML, and PRé (Goedkoop et al., 2009), was selected for this study.

Table 1
Average composition of coke gas and converter gas. Source (Spanish Register of Emissions and Pollutant Sources, 2005).

	Units	Coke gas	Converter gas
CO	%	5.44	68.21
H_2	%	58.14	1.05
CH_4	%	24.36	0.02
C_2H_6	%	0.61	–
N_2	%	5.57	12.95
O_2	%	0.45	0.6
CO_2	%	1.38	13.42
H_2O (VAP)	%	2.21	3.75
Density	Kg/Nm^3	0.434	1.3242
PCI	$Kcal/Nm^3$	3988	2099

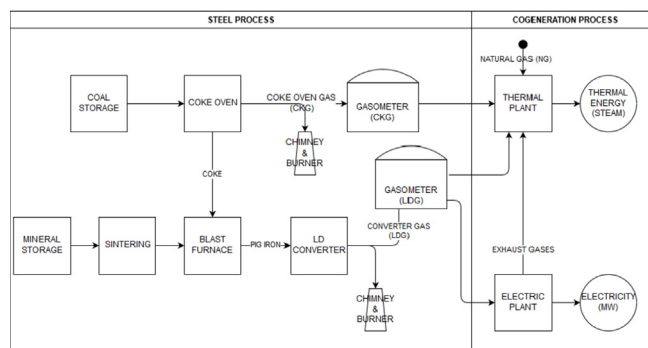**Fig. 1.** Steel gas valorisation process flow diagram.

2.1. Study area

The reference site is the only integrated route steel plant in Spain, including all the facilities starting from ore charging to iron making and coke making. It has an annual production capacity of more than 5 million tons of steel. The following gases are considered for the study:

- Coke gas: The coke used in blast furnaces is manufactured by pyrolysis of coals of a special quality in ovens called coke batteries. In this pyrolysis, at the top of the oven, a gas is obtained with a major content of H_2 (>50%) as well as CH_4 and other inert gases (Spanish Register of Emissions and Pollutant Sources, 2005). It is characterised by having a significant calorific power (about 4000 $kcal/Nm^3$), a little less than half the calorific power of natural gas, a considerable content of potentially polluting substances (SH_2, NH_3, …) and an abundance of heavy oils of organic origin, the energy utilisation of which is difficult.
- Converter gas: the pig iron obtained in the blast furnaces is sent to a type LD converter (Linz-Donawitz) where a portion of the carbon is oxidised forming CO, which in turn is oxidised to other carbonates forming CO_2 to obtain the highest quality steel (Spanish Register of Emissions and Pollutant Sources, 2005). As a result of the reaction between the oxygen blown to the LD converter and carbon, the pig iron contains a gas that has a low calorific value (about 2100 $kcal/Nm^3$, between a quarter and a fifth of that of natural gas) and is quite clean, but due to its high content of CO, is highly toxic.

Blast furnace gas, a by-product of blast furnaces where iron ore is reduced with coke into pig iron, is not being processed by the SGCP at this moment. The gas has a very low heating value of around 900 $kcal/Nm^3$, which on its own is typically not high enough for combustion in a gas engine.

Average compositions of both gases are presented in Table 1.

The studied site is a combined cogeneration plant that produces electricity and steam from the energetic valorisation of steel gases. It combines the technology of cogeneration in a simple cycle, with engines especially adapted for its operation with converter gas, and steam generation in boilers that consume primarily coke gas, converter gas and natural gas in the absence of steel gases. Table 2 shows the energy properties of the three gases and Fig. 1 depicts the process flow.

At the end of the year 2014, the total production of the SGCP had reached 522,881.52 MWh of thermal energy and 92,352.91 MWh of electrical energy. The thermal energy required by the steel factory, approximately 90 tonnes/h, is supplied by three conventional boilers type FDU-3527 with a multifuel burner (coke gas, converter gas or natural gas) with a steam production of 35 tonnes/h and a nominal power of 27 MW, and a recovery boiler type GV-201 with a steam production of 20 tonnes/h and a nominal power of 11 MW. The boilers include an economiser, vaporiser and superheater, as well as a chimney for the evacuation of gases and a by-pass in the economiser. The temperature of the superheated steam is 300 °C, controlled through an attemperator system and an outlet pressure of 1.9 MPa. The water treatment plant consists of four reverse osmosis lines that provide the water supply to the boilers, and two electrodeionization lines that supply the water required in the attemperators. The final quality of the water is as required by the manufacturer of the boilers, having additional means of chemical metering to achieve optimum conditioning.

With regard to the electrical energy, 12 groups of gas engines provide a total net electric power of 20,400 kW, the exhaust gas of which is recovered for the generation of steam. They are designed as compact modular groups, integrated by the engine, the alternator and the auxiliary systems of fuel, cooling, lubrication and boot. The gas engines, designed to operate with converter gas, are four-stroke type with turbocharging and cooling of the air–gas mixture, and an electronically regulated combustion of lean mixture.

The treatment of the exhaust gas from the chimney in the SGCP is similar to that developed in similar processes. As mentioned previously, SO_2 emissions are caused by the combustion of coke gas, but in very low values, such that desulfurisation technology is not necessary. The gas flow is discharged to the base of the chimney

Table 2
Main properties of energy carriers used in the SGCP.

Properties	Coke gas	Converter gas	Natural gas
Amount of fuel consumption (m^3/MWh)	72.97	358.14	48.60
Heating value (kJ/Nm^3)	16.685	8.782	36.123
Energy Content (GJ)	1.22	3.15	1.76
CO_2 Emission factor (kg CO_2/GJ)	42.32	185.47	55.83
Oxidation Factor (kg CO_2/GJ)	1	1	1
SO_2 Emission factor (g SO_2/GJ)	315	0	0
NOx Emission factor (g NOx/GJ)	90	85	62

Table 3
Description of scenarios considered for the study.

| Scenario number	Description
1	Without SGCP utility, so a 100% of the energy delivered from natural gas and steel gases are burned in flame.
2	The SGCP is producing 25% of energy delivered from steel gases, 75% from natural gas.
3	The SGCP is producing 71.3% of energy from steel gases, 28.7% from natural gas (this was the actual consumption of gases in 2014).
4	The SGCP is working exclusively with steel gases. This is the ideal scenario but unattainable because the gasometers' storage capacity is limited.
5	There is a SGCP utility, but due to technical stoppages in the steel plant and the limited capacity of the gasometers, there are no gases available, so all the thermal energy is produced from natural gas.

at a minimum temperature of 135 °C with the objective of avoiding condensation, since this fuel when containing traces of sulfur is very harmful, because, once burned, it forms sulfur oxides that, combined with the condensate water vapour resulting from burning, can form sulfuric acid, which is highly corrosive and detrimental to the conservation of the equipment. The NO_x emissions are determined by the flame temperature, the residence time of the gases in the combustion zone and the oxygen concentration, but, as in the case of SO_2, they are found to be below the limit values and for the moment do not require the application of denitrification techniques.

The surplus coke gas not consumed in the SGCP is employed in other installations at the steel factory, such as in the heating of the plant's coke batteries or the hot mills' furnaces, and finally burn at the torch if no recovery is possible. The untapped converter gas in the SGCP is directly burned at the torch. This is one of the most remarkable things, since the sustainable approach is to minimise the volume of gases burned at the torch.

2.2. Goal and scope

The goal was to assess the environmental impacts of using steel waste gases as fuel in a cogeneration process. The functional unit is 1 MWh of thermal energy produced and delivered to the steel plant. The consideration of this functional unit is based on LCA energy studies like Turconi et al. (2013), Parajuli et al. (2014) or Adams and McManus (2014). In order to assess the SGCP approach, a comparative study for five scenarios (Table 3) of annual operation of the power plant was performed, whereby the variants differed only by the dosage proportions of fuels: natural gas and steel gases (coke gas and converter gas). The proportions are not referred to the volume percentage but to the percentage of contributed energy.

Scenario 3 represents the overall computation of a full year (2014), considering all kinds of situations (maintenance stops, periods of operation with natural gas due to lack of steel gases, mixed operation with steel gas and natural gas, …), so it constitutes the reference scenario for comparison. It is important to consider that steel gases are not always available, depending on the operation program of the steel plant, and the storage capacity, which is limited by the gasometers (two gasometers of 60,000 m^3 as depicted in Fig. 1). The other scenarios represent theoretical situations or specific moments throughout 2014, and they are considered for comparison purposes to assess the convenience of using steel gases in the SGCP. Scenario 1 evaluates the environmental impact of the generation of steel gases as an unavoidable waste in the steelmaking process. Such gases must be burned at the torch before being released into the atmosphere, so its energy value is lost. Scenario 5 represents the hypothetical situation where the steel gases are not being generated due to maintenance stopped in the steel plant or similar circumstances. Nevertheless, thermal and electrical energy is demanded, so it must be generated from natural gas.
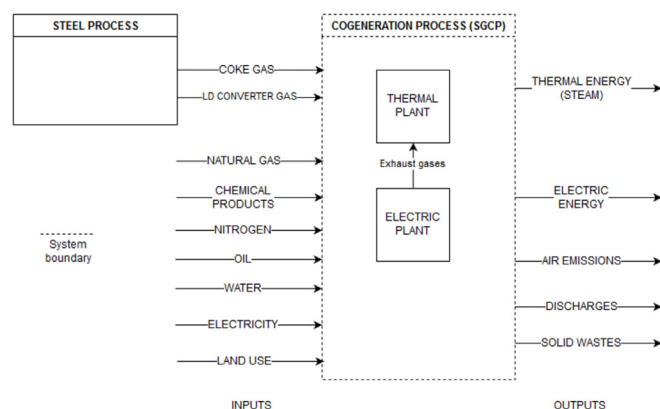
Fig. 2. Steel gases cogeneration process system boundaries.

The process flowchart shown in Fig. 1 is used to identify main inputs and outputs. The system boundaries that define the scope of the study is displayed in Fig. 2. It covers all the operations required for energy production in the SGCP, from upstream raw materials (i.e. gate) to finished product-energy ready to be shipped from the power plant (i.e. gate). The extraction, preparation and transportation of coal and other raw materials necessary for the steel industry, the manufacture of downstream products, their use and their end of life were not included. The internal transport of fuels within the factory is performed by pipeline and the land use of around 8233 m^2 was taken into account. The internal consumption of electricity is covered by shelf-produced electric energy. The importation of electricity is necessary only in cases of an operational disruption. The power plant operates 365 days a year and 24 h each day.

Given that in the cogeneration process two products, steam and electricity, are simultaneously obtained, there is an allocation problem that is solved by substitution thus expanding the system limits following the avoided impacts approach. For example, in addition to electricity, the co-produced heat substitutes a similar thermal energy obtained from another sector. This way, the extractions and emissions related to the substituted heat are avoided. A bonus equal to the emission reduction can therefore be attributed to electricity. For example, Moras (2008) used this method on a cogeneration plant replacing a natural gas engine for electricity and a coal-fired boiler for heat.

2.3. Inventory analysis

Inventory data for the foreground system was taken directly from the studied industrial unit and is based on the year 2014. These are high-quality data, current and representative.

Inventory data corresponding to the background system (raw materials extraction, obtaining of fossil fuels and electricity production) were taken from the Ecoinvent v3.01 database

Table 4
Inventory data for the production of 1 MWh of thermal energy according to the different scenarios (a short description of each scenario is included to improve reading).

Flows	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
	Without SGCP 100% Natural Gas	25% Siderurgical Gases - 75% Natural Gas	71.3% Siderurgical Gases — 28.7% Natural Gas	100% Siderurgical Gases — 0% Natural Gas	Steel plant not working 100% Natural Gas
Inputs					
Natural gas (Nm^3)	169.421144	127.0335033	48.60393613	0	169.421144
Coke gas (Nm^3)	0	25.58417927	72.97064161	102.3627819	0
Converter gas (Nm^3)	0	125.5680235	358.1423952	502.400021	0
Electric energy imported (MW-h)	0	0.008641911	0.003042926	0.002160478	0
Nitrogen (Nm^3)	0.00084278	0.023740331	0.06742254	0.094961323	0.00084278
Cooling water (m^3)	0	0.035753259	0.101539255	0.143013035	0
Water boilers (m^3)	1.91096834	1.910968339	1.910968339	1.910968339	1.91096834
Water treatment chemical products (Kg)	0.01199124	0.011991244	0.011991244	0.011991244	0.01199124
Cooling circuit chemical products (Kg)	0	0.001798	0.005106319	0.007191999	0
Steam circuit chemical products (Kg)	0.00198898	0.001988978	0.001988978	0.001988978	0.01988978
Engines chemical products (Kg)	0	8.4176E-05	0.00023906	0.000336704	0
Oil (Mg)	0	4.8014E-05	0.00013636	0.000192056	0
Infrastructure (m^2)	0	0.015745441	0.015745441	0.015745441	0
Outputs					
Electricity production (MW-h)	0	0.063262655	0.17966594	0.25305062	0
Discharges (m^3)	0	0.609317748	0.609317748	0.609317748	0
SO_2 (Mg)	0.00038352	0.000134465	0.000383509	0.000537996	0
NO_x (Mg)	0.00075636	0.000416659	0.00048577	0.00052874	0.00037935
CO_2 (Mg)	0.97654629	0.47878456	0.73288854	0.89058722	0.34168029
Hazardous waste (Mg)	0	0.000201939	0.000201939	0.000201939	0
Non-hazardous waste (Mg)	0	0.000128136	0.000128136	0.000128136	0

(Frischknecht et al., 2005; Moreno Ruiz et al., 2017; Weidema et al., 2013). The use of this database is very extended, and it was recently considered one of the best available databases (Martínez-Rocamora et al., 2016). Although the last update of the Ecoinvent version used in this study was in 2017 (ecoinvent Version 3, n.d·Moreno Ruiz et al., 2017), the database available for energy generation scenarios corresponds to 2012.

The inventory data of 1 MWh of thermal energy for all the scenarios are summarized in Table 4. The main difference among these scenarios is found in the amount of natural gases replaced by steel gases in order to produce 1 MWh of thermal energy, and the emissions generated in each case. Scenario 3 corresponds to the actual process data gathered from the SGCP during 2014, the column details the actual consumption of natural gas, coke gas and converter gas for that year. Converter gas was the SGCP's most used fuel, followed at quite a distance by coke gas and finally by natural gas.

Emissions represented in scenario 1 include those gases sent and burned at the torch, due to the absence of the cogeneration plant. The pollutants emissions of natural gas exhaust gases when burned at the boilers are 341,680 KgCO2/MWh and 0.379 KgNO$_x$/MWh. While scenario 1 includes emissions to the atmosphere corresponding to the combustion of steel gases at the torch plus the consumption of natural gas for generating the requested energy, in scenario 5 the steel plant is not working, so there are no emissions related to steel waste gases, but thermal and electric energy must still be generated with natural gas.

2.4. Impact assessment categories

The evaluated impact potentials were the categories reflected in Table 5. The choice of these impact categories is based on the fact that they are mostly affected by the substances referred to in the inventory. Moreover, these impact categories cover local, regional and global impacts from steel gas cogeneration. After the preliminary assessment it was determined that only Climate Change,

Table 5
Mid-point impacts.

Impact category	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Climate change (kg CO2 eq.)	1.06E+03	5.14E+02	6.74E+02	6.90E+02	4.66E+02
Ozone depletion (kg CFC-11 eq.)	4.06E-05	2.71E-05	−3.68E-07	−2.93E-05	4.06E-05
Terrestrial acidification (kg SO2 eq.)	1.55E+00	8.44E-01	4.33E-01	−2.33E-01	9.94E-01
Freshwater eutrophication (kg P eq.)	9.00E-03	2.98E-03	−1.13E-02	−3.40E-02	9.05E-03
Human toxicity (kg 1.4-DB eq.)	2.03E+01	1.21E+01	−6.86E+00	−3.11E+01	2.03E+01
Photochemical oxidant formation (kg NMVOC)	1.09E+00	5.81E-01	3.57E-01	−3.21E-02	4.18E-01
Particulate matter formation (kg PM10 eq.)	4.30E-01	2.28E-01	1.03E-01	−1.05E-01	2.48E-01
Terrestrial ecotoxicity (kg 1.4-DB eq.)	1.40E-02	9.47E-03	3.55E-04	−8.98E-03	1.40E-02
Freshwater ecotoxicity (kg 1.4-DB eq.)	1.12E+00	7.06E-01	−2.14E-01	−1.31E+00	1.12E+00
Marine ecotoxicity (kg 1.4-DB eq.)	5.30E-01	2.84E-01	−3.16E-01	−1.15E+00	5.34E-01
Ionising radiation (kBq U235 eq.)	4.54E+00	−1.02E+01	−3.88E+01	−9.79E+01	4.56E+00
Fossil depletion (kg oil eq.)	1.64E+02	−1.05E+00	−1.01E+00	−1.32E+00	1.64E+02

Ozone Depletion, Human Toxicity, Ionising Radiation and Fossil Depletion were fundamental for the study.

The steel gas cogeneration system presented in Figs. 1 and 2 was divided into five steps: raw materials extraction, fossil fuels production, transportation, electricity and atmospheric emissions from the furnaces. The results obtained for each impact category were assessed according to those five steps.

The software used to perform LCA calculations is SimaPro v8.2 (Goedkoop et al., 2016), developed by Pré Consultants. Some examples of works using these method and tools are (Burchart-Korol, 2013) in the field of steel and (Ardolino et al., 2018; Galli et al., 2018) in a more general context.

3. Results and discussion

Table 5 shows the mid-point impacts for each scenario. The main effects are related to Climate change, Ozone depletion, Ionising radiation, Human toxicity and Fossil depletion, depicted in Fig. 3, Fig. 4, Fig. 5, Fig. 6 and Fig. 7. The main contributions to these categories are the consumption of natural gas as fossil resource and the emissions due to the described processes.

Scenario 1 is especially relevant in the five categories as it entails the consumption of natural gas and its emissions, as well as the emission to the atmosphere of the steel gases.

The climate change category (Fig. 3) is directly affected by the emissions. Since this study deals with the analysis of gas utilisation for energy production, this category is especially relevant. In all the scenarios, an important greenhouse gases generation is present, but scenario 1 stands out because it includes the fact that gases generated by the steel production process, and regarded as waste, are burnt in a torch in the steel plant. Therefore, the recycling of

these gases reduces global warming potential as can be deduced from the subsequent scenarios, as it is concluded in (Olmez et al., 2016). This scenario also requires natural gas combustion for the production of thermal energy demanded by the steel plant. The remaining scenarios evaluate a different approach, by including a cogeneration plant which uses these gases to produce thermal energy. Scenarios 3 and 4 have 36% and 35% less impact respectively. However, they are the next more relevant scenarios. They do not compute gas emissions burned in the torch, but they burn an important percentage of steel gases, which is translated into emissions that penalise much more than those of the natural gas. On the other hand, scenarios 2 and 5, have a 52% and 56% lower
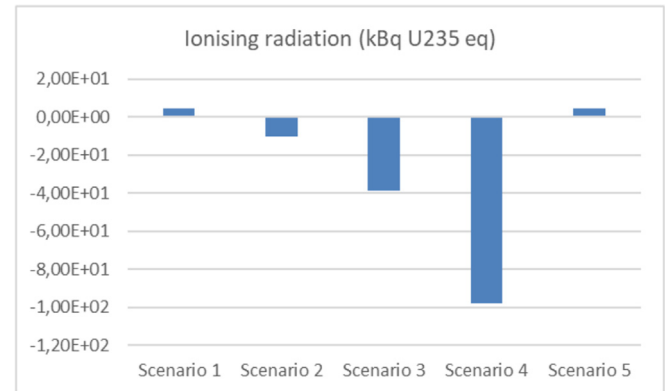
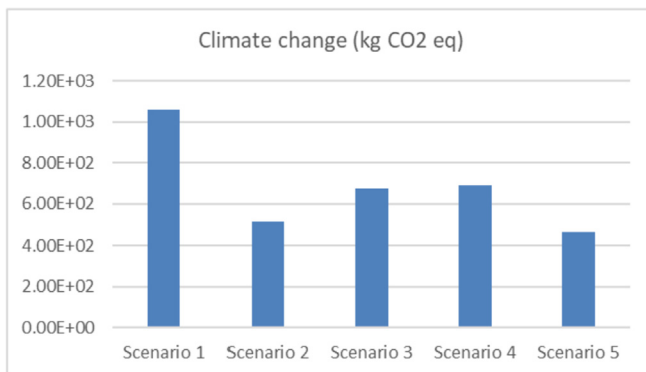**Fig. 5.** Ionising radiation impact of all five scenarios in kBq U235 equivalent.
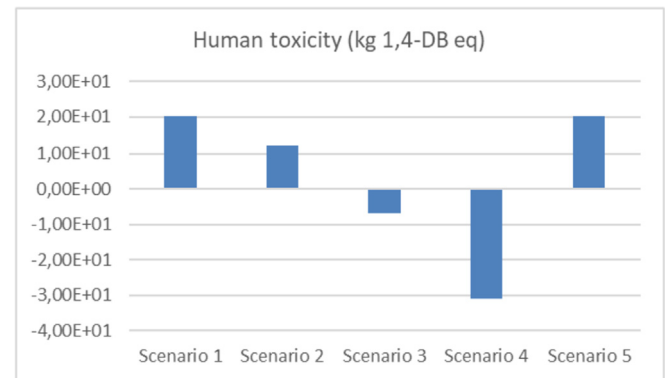
Fig. 6. Human toxicity impact of all five scenarios in kg 1.4 dichlorobenzene equivalent.

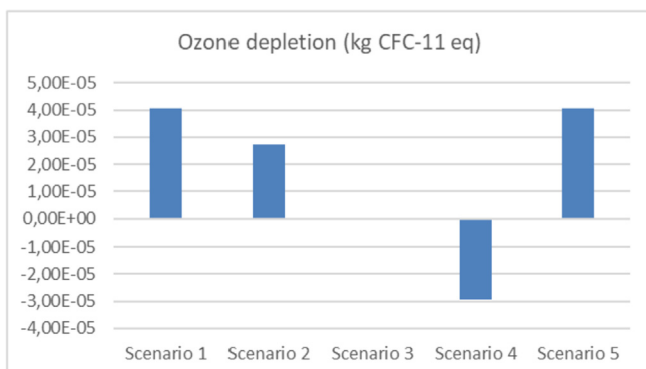**Fig. 3.** Climate change impact of all five scenarios in kg CO_2 equivalent.

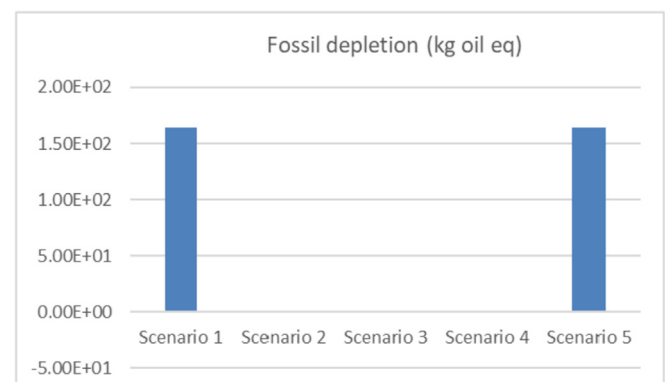**Fig. 4.** Ozone depletion impact of all five scenarios in kg CFC-11 equivalent.

Fig. 7. Fossil depletion of all five scenarios in kg oil equivalent.

contribution to this impact category, since the main energy source in these cases is the much cleaner natural gas.

In the other three categories, Human toxicity (Fig. 6), Ionising radiation (Fig. 5) and Fossil depletion (Fig. 7), natural gas has a fundamental role. Therefore, the greater the natural gas consumption, the greater the impact in these categories will be. A similar correlation is found by Bieda (2011), who stated that the reduction of the amount of power coal leads to saving of primary resources. Thus, scenarios 1 and 5 have the greater scores. Scenario 2, whose energy source is 75% natural gas, also has a remarkable impact in the Human toxicity category. Nevertheless, scenarios 3 and 4, where the contribution of natural gas is 28.7% and null respectively, have a negative score in these categories. This is due to the modelling of the impacts allocation where the electricity produced in the cogeneration process is described as avoided.

The same situation occurs in the category of Ozone depletion with a direct correlation between the natural gas contribution and the impact. This category includes, mainly, the impact produced by industrial chemical agents' molecules, although it also considers methane emissions. Therefore, the natural gas impact in this category is clear. In fact, the aforementioned industrial chemical agents are used in natural gas production and methane emissions are generated. The most relevant stage of the natural gas manufacturing process in this category is the drying gas stage, for which natural gas is consumed to generate the necessary energy and industrial chemical agents are used as well. The reduction of natural gas consumption in scenario 2 with respect to scenario 1 allows, although not exclusively, to produce less impacts, because the generated electricity also contributes to reduce the score. In the same way, in scenario 3 a compensation occurs of the impact generated by the 28.7% of natural gas, whereas in scenario 4 this impact is negative.

The damage evaluation by means of end-points (Fig. 8) reflects how, globally, scenario 1 is the worst. This is due, mainly, to the emissions generated when burning the steel gases at the torch, and the need to be able to emit them in safety conditions. The natural gas consumption needed to generate 1 MW of thermal energy also contributes to worsen this scenario.

The remaining scenarios describe a much smaller impact and the difference between them is very small. The scenario with the smaller impact is the 4th, representing a 77.39% improvement with respect to scenario 1. However, it is necessary to consider that it is an ideal scenario, because it is not operationally viable to burn exclusively steel gases. Regarding impact, scenario 3 is next. This scenario reflects the plant's actual operational situation in the studied year (2014). It entails a 75.70% improvement with respect to scenario 1.

Altogether, the results of scenarios 2, 3 and 4 can be used to perform a sensitivity analysis with respect to the degree of steel gas usage. Thus, it is possible to observe that, the greater the percentage of steel gases contribution, the smaller the impact on fossil resources. This impact is even negative in the fourth scenario due to the effect of the avoided electricity in the cogeneration plant. Nevertheless, the opposite effect is observed with respect to human health and the ecosystem, especially in the climatic change category, due to the increased impact produced by the steel gases whose emissions are more polluting than those of the natural gas.

Scenario 5, in which natural gas is solely used as fuel, is 70.34% less harmful than the first scenario, but less desirable than the scenarios in which steel gases are used. It is necessary to consider that this scenario implies that the steel gases are not burnt but they are not emitted to the atmosphere either, which poses a utopian situation because it would not be feasible to storage them during a prolonged period of time.

An important aspect of study is the one regarding the emissions derived from thermal energy production. The impacts are greater in those scenarios where steel gases are consumed, because they are "dirty" gases with smaller energy efficiency, which generate much more pollutant emissions that those from natural gas. Therefore, scenarios 2 and 5 obtain better results in categories related to emissions, such as Climate Change and Particulate Matter Formation. However, in the final balance, scenarios 3 and 4, where steel gases contribute more than 71.3%, obtain better scores. This is due to the benefit that the use of these gases entails, allowing to reduce natural gas consumption, and at the same time obtaining electricity as a co-product in the cogeneration plant. This effect was already remarked by Olmez et al. (2016) who found that the global warming in the coke making unit had a negative share in environmental impacts because the production of coke oven gas avoids the external energy consumption. This finding is supported also by Guilherme and Castro (2012).

In summary, both the mid-point and the end-point indicate that the usage of steel gases implies an improvement in the sustainability of the steel manufacturing process, because it allows avoiding emissions generated in the torch. These results confirm the conclusion reached by Li et al. (2017) who stated that the option to use the excess by-product gases from the iron making system to generate electricity in a combined cycle power plant is more environmentally friendly than sending the gases to the emission tower and producing the same amount of electricity from coal. Similar conclusions were presented by Bieda (2011).

4. Conclusions

The LCA study demonstrated that the valorisation of coke oven and converter gases to a cogeneration process plant represents an environmental benefit in all the analysed scenarios, even considering that the treatment requires the commissioning of a plant specially designed for it, a smaller yield than if the plant worked with natural gas and more polluting emissions. Minimising natural gas consumption is very important in order to reduce the damage produced by natural resources and ozone depletion. When energy is produced only with waste gases, 169.42 Nm^3/MWh of natural gas are saved (120.82 Nm^3/MWh in normal operating conditions). The worst situation is when the waste gases are burned in the torch. The analysis shows an increase of more than 100 points compared with the studied production scenario with the SGCP in 2014. Waste gases have a worse behaviour with respect to CO_2 emissions than natural gas, but always better than the option to burn them in the torch. Nevertheless, the greater the natural gas consumption, the greater the impact in the Human toxicity, Ionising radiation and Fossil and Ozone depletion categories due to the avoided external energy.

In view of the results, it is possible to design certain actions that involve impact reductions of steel production. It is demonstrated
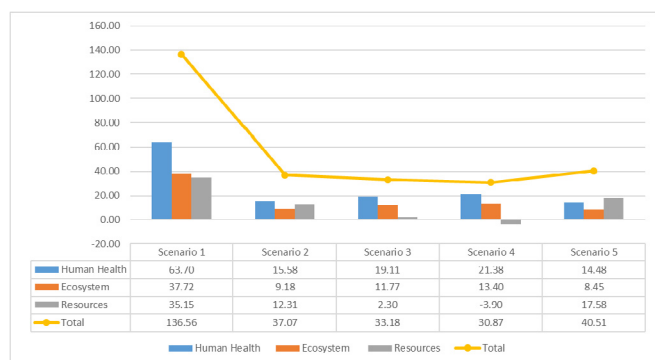

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Human Health	63.70	15.58	19.11	21.38	14.48
Ecosystem	37.72	9.18	11.77	13.40	8.45
Resources	35.15	12.31	2.30	-3.90	17.58
Total	136.56	37.07	33.18	30.87	40.51

Fig. 8. End-points (pt.) of all five scenarios.

that the more waste gas is available for its energetic valorisation, the greater the obtained benefit will be. Therefore, a greater storage capacity in the gas holders would avoid many emissions in torch and would remarkably improve steel gases utilisation.

The present study is an important tool to assist decision making in the management of steel gases by all parties involved in the production process who have several intertwined objectives and sometimes also conflicting interests. Because their energy properties, other downstream processes compete for the utilisation of the waste gases as fuel (i.e. continuous casting or hot rolling furnaces), or even for other kind of products valorisation (i.e. syngas). The results of this study are a valuable contribution for the integration within global optimisation models, for instance with models for optimising the gases distribution or steel plant-level analysis.

In this study, other factors have not been taken into account that undoubtedly would be determinant in the decision-making process, such as economic savings derived from the use of steel gas instead of natural gas or the revenue produced by selling the thermal and electrical energy produced. As further work, a model combining cost information with environmental information is suggested, providing a sensitive analysis tool that would be very useful in the making decisions process.

Conflicts of interest

None.

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